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New functionality development through follower substitution for a leader in open innovation

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ABSTRACT

There has been a paradigm shift to a knowledge-oriented economy in the 21st century. Consequently, there has also been a shift in where innovation typically occurs. This shift has been from the production site toward the process of product diffusion. That is, innovation occurs more frequently at the point at which a product or service is moved into the marketplace where it is immediately modified through customer interaction. In this process, new "functionality" — services, the delivery method or even product changes occur in the diffusion process. Given the need to constantly create new value through new product "functionality" or new "functionality development", firm strategy must address the issue of how to enhance innovation at this new locus — the diffusion process. Sustainable new functionality development over time has become crucial to a firm's competitiveness. In this context, firms have to develop new functionality as early and quickly as possible; leveraging whatever innovation exists in the marketplace. According to theory, the early emergence of functionality development in this context depends on a dynamic system in which the imitator (follower) is constantly substituting for the innovator (leader). This substitution corresponds to the dynamics observed in the process referred to as "open innovation". According to this theory, functionality development through follower substitution for a leader would be critical for a firm's competitiveness in the open innovation environment. Furthermore, open innovation could be a process for sustaining the ongoing creation of new value through functionality development maximizing limited resources. This paper attempts to demonstrate this hypothesis through an empirical analysis of this process of substitution in major innovative goods and services in Japan.

1. Introduction

There has been a paradigm shift to a knowledge-oriented economy in the 21st century. Consequently, there has also been a shift in where innovation typically occurs. This shift has been from the production site toward the process of product diffusion. That is, innovation occurs more frequently at the point at which a product or service is moved into the marketplace where it is immediately modified through customer interaction. Firms must use the interface of customer demand and the creation of new value as well as incorporating existing innovations. The result is an increased level of customized "functionality development" or unique product/service features. Therefore, new "functionality" – services, the delivery method or even product changes – occurs in the diffusion process. Given the need to constantly create a new value through a new product "functionality" or new

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"functionality development", firm strategy must address the issue of how to enhance innovation at this new locus — the diffusion process.

Sustainable new functionality development over time has become crucial to a firm's competitiveness. Firms desiring to remain profitable must develop a process of ongoing innovation in a competitive market maximizing their resources. While rapid innovation creates value increasing profits through increasing demand and often higher prices, obsolescence also happens very quickly. Therefore, sustaining functionality development becomes increasingly important amidst global mega-competition. In this context, firms have to develop new functionality as early and quickly as possible; leveraging whatever innovation exists in the marketplace. According to theory, the early emergence of functionality development in this context depends on a dynamic system in which the imitator (follower) is constantly substituting for the innovator (leader). This substitution corresponds to the dynamics observed in the process referred to as "open innovation". According to this theory, functionality development through follower substitution for a leader would be critical for a firm's competitiveness in the open innovation environment. Furthermore, open innovation could be a process for sustaining the ongoing creation of a new value through functionality development maximizing limited resources. This paper attempts to demonstrate this hypothesis through an empirical analysis of this process of substitution in major innovative goods and services in Japan.

In light of the significant impacts of open innovation [1–3], this paper attempts to demonstrate the significance of the imitator substitution for the innovator in the emergence of functionality development in a diffusion trajectory. The intention of this work is to extend this theory. An empirical analysis focusing on the diffusion trajectory of printers, mobile phones, LCD, innovative goods and services on the web, and PV in Japan is conducted by utilizing the Bass model.

First, an attempt to demonstrate a numerical analysis depicting early functionality development in a diffusion trajectory was conducted. Second, by incorporating governing factors and their magnitude for an increasing trend in innovative goods, the concept of sustainable functionality development was analyzed. Third, utilizing the results of the boundary function in order to satisfy the early functionality development postulate, the dynamism of open innovation was further explained. Fourth, based on these analyses, sustainable functionality development leading to open innovation as a process for firm competitiveness was identified.

Section 2 reviews major relevant literature. Section 3 mathematically develops the concept of the ability to "prolong" or "sustain" functionality development. Section 4 mathematically presents the emergence of functionality development in a diffusion trajectory. Section 5 demonstrates the concept of sustainable functionality development based on the boundary function depicting the conditions for early functionality development. Section 6 identifies the factors contributing to the earlier functionality development emergence when the follower substitutes for the leader. Section 7 briefly summarizes new findings, policy implications and the focus of the future work.

2. Literature review

2.1. Open innovation

Many academics and business practitioners have abandoned the "linear model of innovation" [4–6] in spite of its appealing simplicity and desirability. Instead, recent literature has embraced the theoretical concept of "open innovation" [1,3,7,8] in order to recognize the cooperative nature of partners in industrial innovation, as opposed to the vertical integration of innovation functions in one large corporation [9]. According to the original open innovation theory developed by Chesbrough [1], the term open innovation refers to, "a process, a set of inter-firm relationships, and a cognitive paradigm". He goes onto explain that open innovation "assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as the firms look to advance their technology" [1]. Chesbrough goes on to refine this definition in 2006 to account for knowledge flows and what is widely referred to as "technology spillover". In this context, he defines open innovation as, the intentional use of "inflows and outflows of knowledge to accelerate internal innovation and expand markets" [3]. This is the definition that will be used and defined mathematically in the present study in terms of the ongoing dynamics of "innovator" shifting to "imitator" through these inflows and outflows of knowledge. In particular, the present investigation will be concerned with mathematically describing the process whereby firms use internal and external ideas as they look to advance their technology in the marketplace and remain competitive.

In the past, researchers in the innovation literature have focused on the idea of "technology intelligence [10–12], which refers to how a firm uses its technological environment to support internal innovation. In response to the increasing acquisition of external technology, some studies have additionally pointed to the need for technology acquisition intelligence [10,11,13,14]. In the technology management literature, researchers have embraced the notion that technology acquisition from external sources is important [15]. This is particularly true of studies comparing developing and developed countries. Similar to the innovation literature, technology management literature has evolved from R&D management to strategic technology management in terms of three main dimensions: scope (corporate and strategic focus of R&D), view of technology (tool versus source of value for business), and associated issues (produce development, diversification and integration of technology) [16,17]. Therefore, the technology management literature has also evolved from a linear, stable and predictable model to a discontinuous process at the strategic level. Based on this foundation, researchers have moved toward incorporating the theory of dynamic capabilities into the basic understanding of the process of innovation and technology management [17]. The concept of dynamic capabilities converges with the concept of open innovation in that both, by definition, involve internal and external flows of knowledge to accelerate technological innovation in a dynamic way [9,18].

Based on Chesbrough's definition of open innovation [3], the present study will confirm and expand the theory of open innovation by mathematically analyzing the interaction of specific factors. The present study builds on both the innovation and technology management literature by capturing the importance of strategic technological change through dynamic capabilities and through open innovation. It takes into account the difficulty of forecasting technological change and the firms need to closely understand and capture knowledge from the external environment.

2.2. Mathematical modeling of innovation, technology spillover and diffusion

An epidemic function has been popularly used for the analysis of the diffusion trajectory of innovation [19]. This epidemic function identifies the contagion process similar to epidemic behavior [20] and exhibits sigmoid growth. Since Verhulst [21] introduced the logistic model depicting sigmoid growth, a number of studies have demonstrated this model in analyzing the diffusion trajectory. The diffusion trajectory of high-technology products has also been demonstrated to correspond to this trajectory.

Utilizing the logistic growth function, Watanabe et al. [22] postulated that the ratio of carrying capacity to the level of diffusion represents the extent of functionality development. The emergence of innovation leads to new functionality development and the efforts for maintaining the level of functionality development creates successive innovations.

Furthermore, this functionality development can be generated by technology stock which consists of a firm's own technology stock and assimilated technology "spilled over" from the marketplace. Watanabe et al. [23] demonstrated that the spillover effect is significant for functionality development and, thus, effective utilization of spillover technology is an important strategy for a firm for its competitiveness. The effective utilization of spillover technology is proportional to the potential spillover pool and the ability of a firm to leverage its potential benefits [24]. Cohen and Levinthal [25,26] developed a concept of absorptive capacity as the ability to recognize the value of external information, assimilate it and apply it to commercial ends. Watanabe et al. [27] then developed a mathematical equation to measure this assimilation capacity in this technology spillover dynamism.

While there has been a variety of diffusion models depicting the diffusion trajectory of innovation, Bass model [28] enables the identification of the role of innovator and imitator in leading innovation diffusion.

3. Functionality development in a diffusion trajectory

3.1. Functionality development concept

The improvement of goods and services or even the performance of the production processes through innovation can be defined as functionality development [23].

Diffusion of innovative goods and services is induced by their ability to dramatically improve the performance of production processes, goods and services through innovation.

Based on this postulate, Watanabe et al. [29] demonstrated that the state of functionality development (FD) can be traced using the diffusion trajectory depicted by the following epidemic function:

$$\frac{dY}{dt} = aY\left(1-\frac{Y}{N}\right) \tag{1}$$

where Y: production of innovative goods and services; N: carrying capacity; and a: velocity of diffusion.

Incorporating the contribution of innovator and imitator to the diffusion trajectory, Eq. (1) can be developed into the following Bass model:

$$\frac{dY}{dt} = (pN + qY)\left(1-\frac{Y}{N}\right) \tag{2}$$

where p: innovator; and q: imitator parameter.

While Y continues to diffuse as far as it incorporates functionality development, since Eqs. (1) and (2) suggest $\frac{dY}{dt} = 0$ when Y reaches N, Y stops diffusing when it reaches the level of carrying capacity N.

This termination can be attributed to the obsolescence of the functionality development or new product. Therefore, the degree of functionality development can be identified by the potential capacity before reaching the obsolescence stage which can be measured by the ratio of carrying capacity to the level of diffusion as follows:

$$\text{Degree of } FD = {}^{N}/_{Y} \tag{3}$$

Since Eq. (2) can be developed into the following diffusion trajectory, it can be depicted by Eq. (4), and the FD can be depicted by Eq. (5):

$$Y(t) = \frac{N\left(1-e^{-(p+q)t)}\right)}{1+\frac{q}{p}e^{-(p+q)t}} \tag{4}$$

$$FD(t) = \frac{N}{Y(t)} = \frac{N}{\frac{N\left(1-e^{-(p+q)t}\right)}{1+\frac{q}{p}e^{-(p+q)t}}} = \frac{1+\frac{q}{p}e^{-(p+q)t}}{1-e^{-(p+q)t}} \tag{5}$$

3.2. The effort to prolong functionality development

Eq. (5) suggests that functionality development tends to decline over time. Firms' management strategy involves efforts to prolong a high level of functionality development. These efforts can be identified as follows:

In the Bass model, q/p demonstrates this "prolonging ability" as shown by the following mathematical development:

Provided that $q/p \equiv x$ and $e^{-(p+q)t} \equiv y$, FD can be expressed as follows:

$$FD = \frac{1+xy}{1-y} \qquad (6-1)$$

Differentiation of FD with respect to x,

$$\frac{dFD}{dx} = -\frac{-\frac{dy}{dx}(1+xy)}{(1-y)^2} + \frac{y + x\frac{dy}{dx}}{(1-y)} = \frac{(1+x)\frac{dy}{dx} + y - y^2}{(1-y)^2} \qquad (6-2)$$

Since $\frac{dy}{dx} = -\left[p + \frac{dp}{dx}(1+x)\right]ty$,

$$\frac{dFD}{dx} = \frac{y}{(1-y)^2}\left[1-\left\{p + \frac{dp}{dx}(1+x)\right\}(1+x)t - y\right] = \frac{y}{(1-y)^2}\left[1-p(1+x)t - \frac{dp}{dx}(1+x)^2 t - y\right] \qquad (6-3)$$

Since $e^{-(p+q)} = y^{-t}$ and $p+q \ll 1$, y can be approximated as follows:

$$y = \left[e^{-(p+q)}\right]^t = [1-(p+q)]^t = [1-p(1+x)]^t \approx 1-p(1+x)t \qquad (6-4)$$

Therefore, Eq. (6-3) can be developed as follows:

$$\frac{dFD}{dx} = -\frac{y(1+x)^2}{(1-y)^2} t \cdot \frac{dp}{dx} > 0 \qquad (6-5)$$

Since inequality (Eq. (6-5))[1] demonstrates that functionality development increases as the ratio of q/p increases, q/p can be identified as the "prolonging ability."

Consequently, the prolonging ability and its contribution to functionality development in the Bass model can be observed.

4. The emergence of functionality development in a diffusion trajectory

Since functionality development decreases as time passes, the timing for the emergence of functionality development and its governing factors are critical for firm strategy.

4.1. Timing of functionality development emergence

Based on the Bass model, Norton and Bass [30] showed the substitution effect of high-technology products by taking the secondary derivative of $Y(t)$ which incorporates these high-technology products. They considered the maximum/minimum level of the secondary derivative as the point of substitution for high-technology products since this level corresponds to the inflection point of the diffusion. Norton and Bass [30] demonstrated this postulate by an empirical analysis utilizing the diffusion trajectory of semiconductor product DRAM over the period 1974–1983.

Inspired by Bass [28] and Rogers [31], Mahajan et al. [32] analyzed the categories of adopters for innovative goods ("adopter categories") by taking the tertiary derivative of $Y(t)$ which enables the determination of the sizes of "adopter categories" by time as illustrated in Fig. 1. They analyzed inflection points of the diffusion as indicated in the right hand side of the figure and the corresponding "adopter categories."

As postulated by Mahajan et al. [32], the diffusion trajectory shifts from increasing diffusion velocity to decreasing diffusion velocity at the inflection point $t^{\#}$. Furthermore, the increasing diffusion velocity changes from "increasing faster" to "increasing slowly" at the earlier inflection point of the first derivative t_1. Also, the decreasing diffusion velocity shifts from "decreasing slowly" to "decreasing quickly" at the later inflection point of the first derivative t_2. Corresponding to these inflection points, the diffusion trajectory can be classified as (i) early adopters $(0-t_1)$, (ii) early majority $(t_1-t^{\#})$, (iii) late majority $(t^{\#}-t_2)$, and (iv) laggards

[1] Since increase in x demonstrates a shift from p to q, dp/dx demonstrates a negative value (see Table 2 in Section 5).

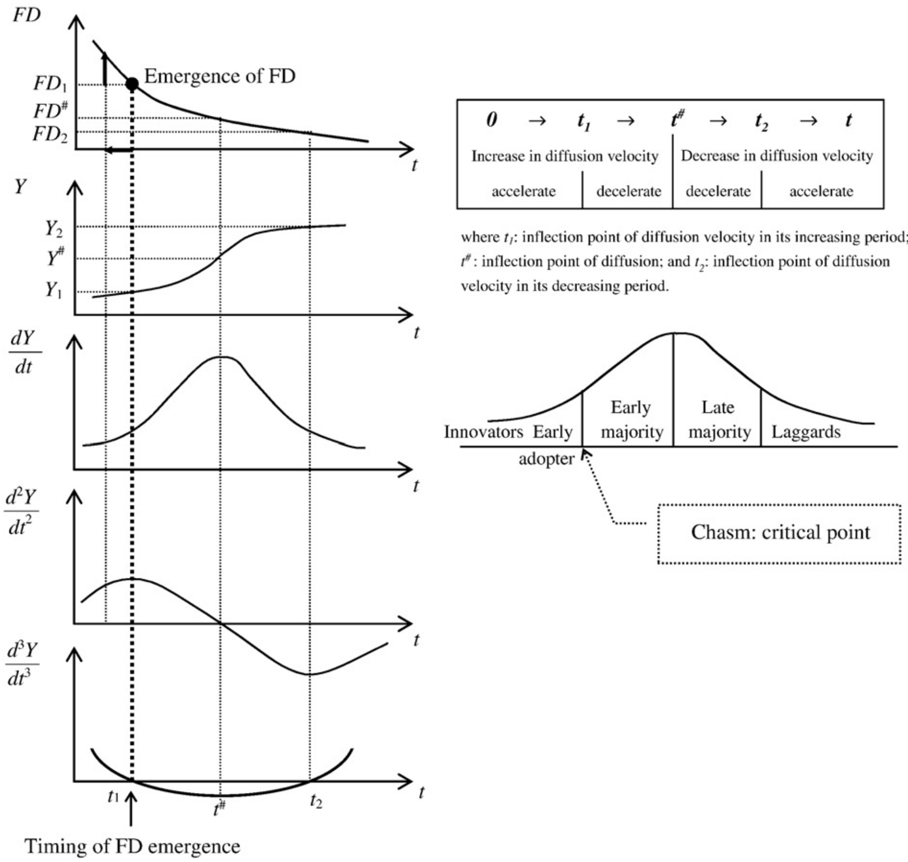

Fig. 1. Level and timing of inflection in a diffusion trajectory.

$(t_2 - \infty)$. As demonstrated in Fig. 1, they examined the inflection point t_1 corresponding to the transition from an increasing to a decreasing trend in diffusion velocity and demonstrated that this time t_1 can be identified as $d^3Y/dt^3 = 0$. Furthermore, inflection points $t^\#$ and t_2 are also identified as tabulated in Table 1.

Table 1
Timing, Level and FD between Bass Model and Logistic Growth Model.

	Bass model	Logistic growth model
t_1	$-\frac{1}{(p+q)} ln\left[\left(2+\sqrt{3}\right)\frac{p}{q}\right]$	$\frac{ln\left(2-\sqrt{3}\right)b}{a}$
$t^\#$	$-\frac{1}{(p+q)} ln\left(\frac{p}{q}\right)$	$\frac{lnb}{a}$
t_2	$-\frac{1}{(p+q)} ln\left[\frac{1}{\left(2+\sqrt{3}\right)}\frac{p}{q}\right]$	$\frac{ln\left(2+\sqrt{3}\right)b}{a}$
Y_1	$N\left[1-\left(2+\sqrt{3}\right)\frac{p}{q}\right] / \left(3+\sqrt{3}\right)$	$N / 3+\sqrt{3}$
$Y^\#$	$\frac{N}{2}\left(1-\frac{p}{q}\right)$	$N/2$
Y_2	$N\left[1-\left(2-\sqrt{3}\right)\frac{p}{q}\right] / \left(3-\sqrt{3}\right)$	$N / 3-\sqrt{3}$
FD_1	$\left(3+\sqrt{3}\right) / \left[1-\left(2+\sqrt{3}\right)\frac{p}{q}\right]$	$3+\sqrt{3}$
$FD^\#$	$2 / \left(1-\frac{p}{q}\right)$	2
FD_2	$\left(3-\sqrt{3}\right) / \left[1-\left(2-\sqrt{3}\right)\frac{p}{q}\right]$	$3-\sqrt{3}$

Moore [33] pointed out that there exists a deep trench repelling new ventures start-up called "chasm"[2] that lies between minor and major markets corresponding to the early adopters and the early majority of the diffusion trajectory as illustrated in Fig. 1.

These rationales demonstrated by Rogers [31], Mahajan et al. [32], Moore [33], and Watanabe et al. [23] suggest that functionality development emergence can be identified as the ability to overcome the barrier of the market by new innovation.

Consequently, it can be concluded that the emergence of FD occurs at a certain point corresponding to "crossing the chasm" and also that the timing of FD emergence can be identified as the earlier inflection point of the first derivative of t_1. Furthermore, Fig. 1 demonstrates that the early emergence of FD enhances the higher level of FD.[3]

This earlier emergence of FD leads to a firm's competitiveness corresponding to not only technology-oriented but also market-oriented adoption.

Rogers [31] postulated that the breeding stage of new innovations can be divided into five stages: the innovator (2.5% of the life time), early minority (13.5%), early majority (34%), late majority (34%) and laggard (16%).

The chasm corresponds to the point when new functionality development emerges. The life time confronting with the chasm equivalents to 16%, while the similar life time when FD emerges equivalents to $[21\% - 1/(1+b)]$ suggesting that when the initial level of the diffusion $[1/(1+b)] = 0.05$, Mahajan's point, corresponds exactly to the point of the chasm (see Appendix 1).

Table 1 compares the timing, level of diffusion and FD depicted by those of Bass model.

4.2. Governing factors accelerating the emergence of functionality development

Firms' efforts in prolonging FD are managed by their technology strategy represented by their gross technology stock T. Generally, T increases proportional to time t as demonstrated by Eq. (7) (see Appendix 2):

$$T_t = \alpha + \beta t \tag{7}$$

where α and β ($\alpha, \beta > 0$): coefficients.

Therefore, $Y(t)$ can be depicted by the following equation:

$$Y(t) = \frac{N}{1 + be^{-at}} = \frac{N}{1 + b'e^{-a'T_t}} \tag{8}$$

where a' and b': coefficients for velocity of diffusion driven by T_t, and initial state of diffusion, respectively.

Since the following mathematical development explains the relationship between t and T, the diffusion trajectory indicated by t can be depicted as a function of T.

Synchronizing Eqs. (7) and (8) leads to the following equation:

$$Y(t) = \frac{N}{1 + b'e^{-a'T_t}} = \frac{N}{1 + b'e^{-a'(\alpha + \beta t)}} = \frac{N}{1 + b'e^{-a'\alpha} \cdot e^{-a'\beta t}} = \frac{N}{1 + b''e^{-a''t}} \tag{9}$$

where $a'' = \alpha\beta$ and $b'' = b'e^{-a'\alpha}$.

With the foregoing understanding, FD function can be developed into a multi-logistic growth model as a function of gross technology stock T.

Consequently, functionality development FD(t) can be depicted by the following equation:

$$FD(t) = N / Y(t) = 1 + b'e^{-a'T_t} \approx 1 + b'(1 - a'T)_t = \sum_{j=1}^{n} \left[1 + b_j\left(1 - a_j T_t\right)\right] \equiv \sum_{j=1}^{n} FD_j(T_t) \tag{10}$$

where $a_j = \frac{a'b'}{b_j} \cdot P_j$, $b_j = [b' - (n-1)] \cdot P_j$ and $\sum_{j=1}^{n} P_j = 1$.

These postulates can be applied also to the Bass model and decomposed to the logistic growth model.[4]

Gross technology stock T consists of indigenous technology stock T_i and assimilated spillover technology zT_s as follows:

$$T = T_i + zT_s \tag{11}$$

where z: assimilation capacity[5]; T_i: indigenous technology; and T_s: technology spillover pool.

The level of gross technology stock (T) increases in a cascading way depending on the assimilation capacity (z) as illustrated in Fig. 2. Therefore, its level differs depending on the level of zT_s, particularly the level of z given the exogenously governed nature of T_s.

[2] Moore [33] described the chasm impediment as an information discrepancy. Prompted by his postulate, "crossing the chasm" when an innovation crosses the early adopter category to another category ("appreciates benefits of technology" and "a key to penetration") successfully.

[3] Rogers [31] and Mahajan et al. [32], pointed out "earlier adopters" who have higher levels of "opinion leadership" and have a greater "usage propensity," respectively. In line with these rationales, earlier emergence of FD leading to the higher level of FD implies that an earlier adoption to the market is critical strategy.

[4] $Y(t) = \frac{N\left(1 - e^{-(p+q)t}\right)}{1 + \frac{q}{p}e^{-(p+q)t}} = \frac{N}{1 + \frac{q}{p}e^{-(p+q)t}} - \frac{\frac{p}{q}N}{1 + \frac{p}{q}e^{(p+q)t}} = \frac{N}{1 + b_1 e^{-a_1 t}} - \frac{b_2 N}{1 + b_2 e^{-a_2 t}}$ where $a_1 = p + q$, $a_2 = -(p+q)$, $b_1 = q/p$, and $b_2 = p/q$.

[5] $z = \frac{1}{1 + \frac{\Delta T_s / T_s}{\Delta T_i / T_i} \cdot \frac{T_i}{T_s}}$ where $\Delta T_i = \frac{dT_i}{dt}$. See Watanabe et al. [27].

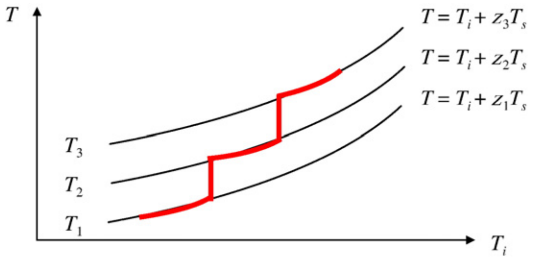

Fig. 2. Acceleration of FD emergence depending on assimilation capacity.

Fig. 3 indicates that a higher level of diffusion enables the earlier timing for the emergence of FD at a higher level.

4.3. Classification of the functionality development trajectory

As reviewed in the preceding subsection and also illustrated in Fig. 2, since the level of T increases in a cascading way depending primarily on assimilation capacity z, and the timing of FD emergence is accelerated as T increases, the level of FD can be classified into three categories depending on assimilation capacity z. These conditions can be described as: (i) decreasing FD ($z=0$), (ii) constant FD ($dz/dT_i=0$), and (iii) sustainable FD ($dz/dT_i>0$) as illustrated in Fig. 4. A self-propagating assimilation capacity increase leads to sustainable FD. The third case "sustainable FD" can be attributed to a self-propagating assimilation capacity increase leading to the ability to prolong FD. This corresponds to the prolonging ability q/p increase in the Bass model as reviewed in Section 3.

Since FD is enhanced corresponding to the higher level of T [23], in the case of the co-evolutionary dynamism between zT_s and T (T enhances as zT_s increases which in turn induces further zT_s), multi-logistic growth leads to sustainable functionality development trajectory. The level of diffusion increases as assimilated spillover technology increases leading to a higher level of FD as it emerges. This trajectory can be traced as an envelope curve of functionality development as illustrated in Fig. 4. Sustainable functionality development can be anticipated when the level of functionality development that emerged in the successive wave is

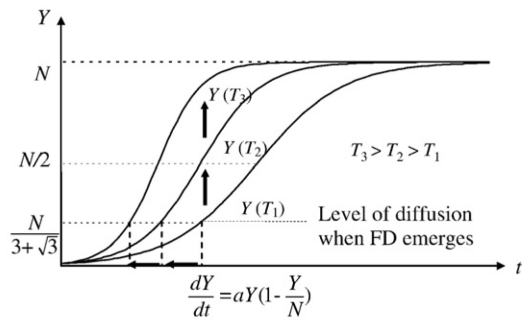

Fig. 3. Diffusion trajectory and functionality development of innovative goods.

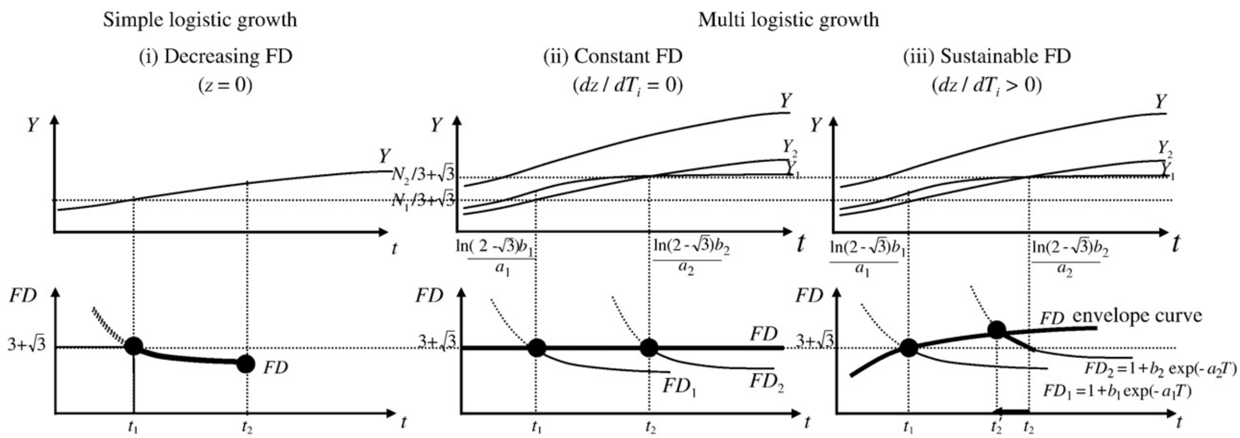

Fig. 4. Comparison of growth trajectory between simple and multi-logistic growths.

more than the level of the preceding wave. This happens when assimilated spillover technology increases as innovation advances ($dz/dT_i>0$), and this can be attributed to the effects of cumulative learning from the preceding innovation [34].

5. Sustainable functionality development

An empirical analysis taking the diffusion trajectory of high-technology in the Bass model was conducted. The goal was to demonstrate sustainable functionality development through the early emergence of FD in a dynamic game between innovator and imitator.

As illustrated in Fig. 1, the timing of FD emergence can be identified as t_1 satisfying the following condition:

$$\frac{d^3Y}{dt^3} = 0$$

Given that $q/p \equiv x$, and $\frac{1}{p+q} \equiv \nu$, this time t_1 in the Bass model can be depicted as follows:

$$t_1 = -\frac{1}{(p+q)} ln\left[\left(2+\sqrt{3}\right)\frac{p}{q}\right] = -\nu ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] = \nu ln\left[\frac{x}{\left(2+\sqrt{3}\right)}\right] \tag{12}$$

where t_1: timing of functionality development emergence.

5.1. Requirement for earlier functionality development emergence

Since q/p demonstrates the ability to prolong FD, the following analysis examines whether an increase in q/p contributes to a decrease in t_1. This can be examined as follows:

$$\frac{dt_1}{dq/p} = \frac{dt_1}{dx} = \frac{d\nu}{dx} ln\left[\frac{x}{\left(2+\sqrt{3}\right)}\right] + \frac{\nu}{x} \tag{13}$$

where $\nu = \frac{1}{p(1+x)}$, $\frac{\nu}{x} = \frac{1}{p(1+x)x}$, and $\frac{d\nu}{dx} = \frac{-\left[(1+x)\frac{dp}{dx}+p\right]}{[p(1+x)]^2}$.

Therefore, Eq. (13) can be developed as follows:

$$\frac{dt_1}{dq/p} = \frac{-\left[(1+x)\frac{dp}{dx}+p\right]}{[p(1+x)]^2} ln\left[\frac{x}{\left(2+\sqrt{3}\right)}\right] + \frac{1}{px(1+x)} = \frac{1}{px(1+x)}\left[1+\frac{\left[(1+x)\frac{dp}{dx}+p\right] ln\left[\frac{(2+\sqrt{3})}{x}\right] x}{p(1+x)}\right] \tag{14}$$

In case when $W(x) = \frac{\left[(1+x)\frac{dp}{dx}+p\right] ln\left[\frac{(2+\sqrt{3})}{x}\right] x}{p(1+x)} < -1$,

$$\frac{dt_1}{dq/p} < 0 \tag{15}$$

From the above analysis, the increase in q/p induces FD to emerge quickly, leading to a more sustainable FD curve. Therefore, $\frac{dt_1}{dq/p} < 0$ are the necessary conditions for earlier functionality development emergence.

5.2. Boundary satisfying earlier functionality development emergence

In order to indentify the boundary condition satisfying earlier FD emergence in the Bass model, the following analysis was attempted.

$$\begin{aligned} \frac{dt_1}{dq/p} < 0 &\Leftrightarrow \frac{\left[(1+x)\frac{dp}{dx}+p\right] ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] x}{p(1+x)} < -1 \Leftrightarrow \frac{(1+x)\frac{dp}{dx} ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] x}{p(1+x)} + \frac{p ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] x}{p(1+x)} < -1 \\ &\Leftrightarrow \frac{\frac{dp}{dx} ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] x}{p} + \frac{ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] x}{(1+x)} < -1 \end{aligned} \tag{16}$$

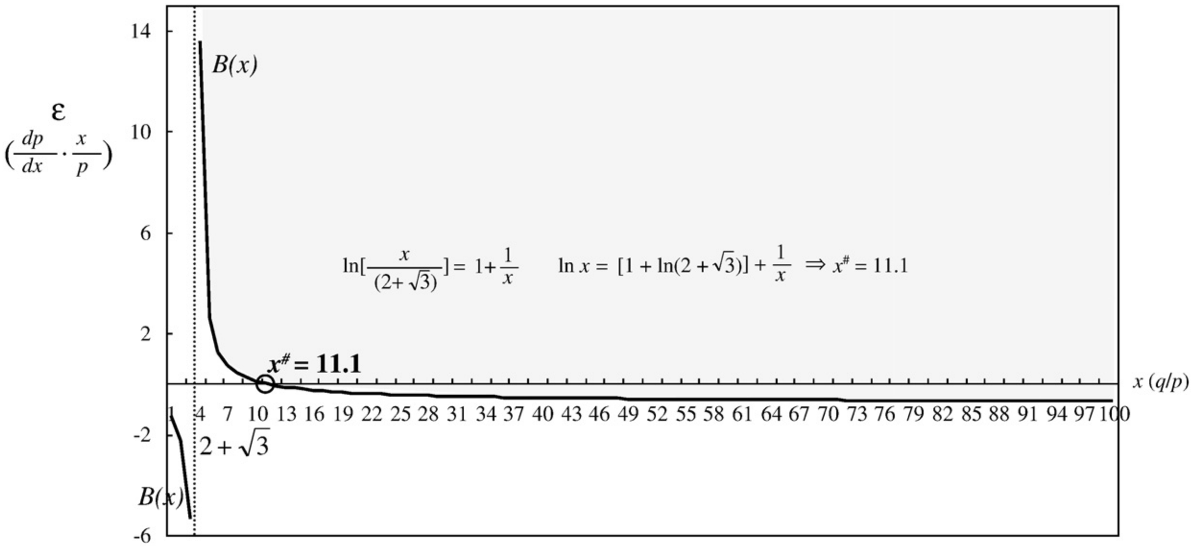

Fig. 5. Boundary function satisfying earlier FD emergence.

If $1 < x < 2 + \sqrt{3}$, then $ln\left(\frac{2+\sqrt{3}}{x}\right) > 0$, and thus

$$\frac{dt_1}{dq/p} < 0 \Leftrightarrow \frac{dp}{dx}\frac{1}{p} < -\frac{1}{ln\left[\frac{(2+\sqrt{3})}{x}\right]x} - \frac{1}{(1+x)} \Leftrightarrow \varepsilon \equiv \frac{dp}{dx}\frac{x}{p} < -\frac{1}{ln\left[\frac{(2+\sqrt{3})}{x}\right]} - \frac{x}{(1+x)} \tag{17}$$

where ε: x elasticity to p.

If $x > 2 + \sqrt{3}$, then $ln\left(\frac{2+\sqrt{3}}{x}\right) < 0$, and thus

$$\frac{dt_1}{dq/p} < 0 \Leftrightarrow \frac{dp}{dx}\frac{1}{p} > -\frac{1}{ln\left[\frac{(2+\sqrt{3})}{x}\right]x} - \frac{1}{(1+x)} \Leftrightarrow \varepsilon \equiv \frac{dp}{dx}\frac{x}{p} > -\frac{1}{ln\left[\frac{(2+\sqrt{3})}{x}\right]} - \frac{x}{(1+x)} \tag{18}$$

Therefore, the boundary function distinguishing the trajectory satisfying earlier FD emergence from the diffusion trajectory can be depicted as follows:

$$B(x) = -\frac{1}{ln\left[\frac{(2+\sqrt{3})}{x}\right]} - \frac{x}{(1+x)} \tag{19}$$

where $B(x)$: boundary function, and $x > 1, x \neq 2 + \sqrt{3}$.

From the boundary function $B(x)$, the following conditions for satisfying earlier FD emergence $\frac{dt_1}{dx} < 0$ can be demonstrated as follows:

If $1 < x < 2 + \sqrt{3}$, then $\varepsilon < B(x)$
and if $x > 2 + \sqrt{3}$, then $\varepsilon > B(x)$

Therefore, the areas that satisfy the necessary condition $\frac{dt_1}{dx} < 0$ are illustrated in Fig. 5.

Furthermore, in order to accomplish open innovation, which means dynamically shifting from p to q as necessary, the condition $\frac{dp}{dx} < 0$ should also be satisfied.

Areas which satisfy both conditions $\frac{dp}{dx} < 0$ and $\frac{dt_1}{dx} < 0$ can be identified as areas III and IV in Fig. 6.

The above classification is summarized in Table 2.

Table 2 suggests that the area which satisfies both conditions $\frac{dp}{dx} < 0$ and $\frac{dt_1}{dq/p} < 0$ with a value for q/p larger than 10 value p can be identified as area III.[6]

[6] Based on the analyses of Bass [28], Mahajan et al. [32], and authors' empirical analyses, generally the value of x (q/p) is larger than 10. Thus, following analyses focus on area III.

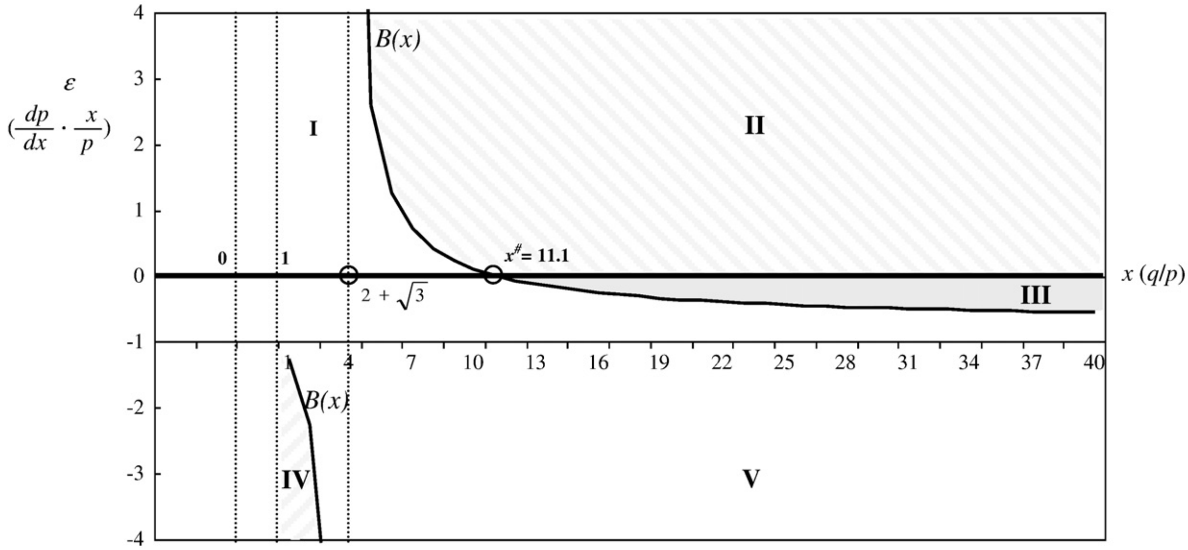

Fig. 6. Boundary function.

6. Requirement for sustainable functionality development

6.1. Imitator substitutes for innovator

Given that x is large enough (see Appendix 3), then the necessary conditions for $\frac{dp}{dx}<0$ and $\frac{dt_1}{dx}<0$ (area III) are depicted as follows:

$$-1<\frac{dp}{dx}\cdot\frac{x}{p}<0 \Leftrightarrow -\frac{p}{x}<\frac{dp}{dx}<0 \tag{20}$$

This condition leads to the following condition:

$$-1<\frac{dp}{dx}\cdot\frac{x}{p}<0 \Leftrightarrow -1<\frac{dlnp}{dlnx}<0 \Leftrightarrow -1<\frac{1}{\frac{dlnx}{dlnp}}<0 \Leftrightarrow \left(\frac{-dlnx}{dlnp}\right)\times(-1)<\left(\frac{-dlnx}{dlnp}\right)\times\frac{1}{\frac{dlnx}{dlnp}}<0 \Leftrightarrow \frac{dlnx}{dlnp}<-1 \tag{21}$$

$$\Leftrightarrow \frac{d(lnq-lnp)}{dlnp}<-1 \Leftrightarrow \frac{dlnq}{dlnp}<0 \Leftrightarrow \frac{dq}{dp}\cdot\frac{p}{q}<0$$

This inequality suggests there is a substituting relationship between p and q.

Furthermore, utilizing the inequality $\frac{dp}{dx}<0$, the substituting dynamism between p and q can be identified as follows:

$$\frac{dp}{dq/p}<0 \Leftrightarrow \frac{dq/p}{dp}<0 \Leftrightarrow \frac{dq/p}{dp}\cdot\frac{p}{q/p}<0 \Leftrightarrow \frac{dlnq/p}{dlnp} = \frac{d(lnq-lnp)}{dlnp} = \frac{dlnq}{dlnp}-1<0 \Leftrightarrow \frac{dlnq}{dlnp}<1 \tag{22}$$

$$\Leftrightarrow \frac{\frac{d}{dt}lnq}{\frac{d}{dt}lnp}<1 \Leftrightarrow \frac{\Delta q/q}{\Delta p/p}<1$$

Since $\Delta p/p<0$,

$$\frac{\Delta q/q}{\Delta p/p}\cdot\left(\frac{-\Delta p}{p}\right)<1\cdot\left(-\frac{\Delta p}{p}\right)-\frac{\Delta q}{q}<-\frac{\Delta p}{p} \Leftrightarrow \frac{\Delta q}{q}>\frac{\Delta p}{p} \Rightarrow p\to q \tag{23}$$

Table 2
Conditions of boundary function by area.

Area	$\frac{dp}{dx}$	$\frac{dt_1}{dx}$	x	ε
I	+	+	$1<x<2+\sqrt{3}$	$\varepsilon>0$
II	+	–	$x>2+\sqrt{3}$	$\varepsilon>0$
III	–	–	$x>11.1$	$-1<\varepsilon<0$
IV	–	–	$1<x<2+\sqrt{3}$	$\varepsilon<0$
V	–	+	$x>2+\sqrt{3}$	$\varepsilon<0$

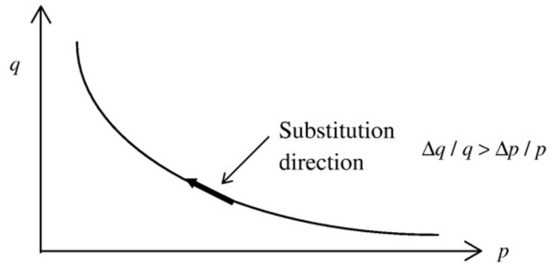

Fig. 7. Scheme of the substitution direction from p to q.

Therefore, substitution direction is observed from p to q as illustrated in Fig. 7.

Based on these observations, sustainable functionality development depends on the early emergence of functionality development. Furthermore, the early emergence of FD depends on imitator (follower) substitution for an innovator (leader). This substitution corresponds to the dynamism triggered by open innovation. Consequently, we can conclude that sustainable functionality development leads to the process of open innovation described by the theories presented earlier.

6.2. Sustainable functionality development by innovations

In order to demonstrate this postulate, an empirical analysis focusing on the diffusion trajectories of several of Japan's major innovative goods and services such as printers, mobile phones, liquid crystal display (LCD), innovative goods and services on the web, and photovoltaic solar cells (PV) was conducted. To analyze the substitution dynamism between innovator and imitator leveraging, the cumulative learning of the preceding innovation for sustainable functionality development was analyzed in Fig. 4. This was based on the concept of the Bi-logistic growth model [35] which analyzed two co-existing diffusion trajectories. Therefore, the following Bi–Bass model was developed.

$$Y(t) = \frac{N_1\left(1-e^{-(p_1+q_1)t}\right)}{1+\frac{q_1}{p_1}e^{-(p_1+q_1)t}} + \frac{N_2\left(1-e^{-(p_2+q_2)t}\right)}{1+\frac{q_2}{p_2}e^{-(p_2+q_2)t}} \tag{24}$$

Notations 1 and 2 represent preceding and succeeding innovations, respectively.

Table 3 summarizes the results of the diffusion parameters in Japan's major innovative goods and services by this model.

Using the results above and Eq. (19), the positions of the respective innovative goods and services were examined with the boundary function $B(x)$ which distinguishes the trajectories and satisfies the condition of an early FD emergence. Therefore, these new positions were identified in Fig. 8.

Fig. 8 demonstrates that while the latest innovations in goods and services such as LBP/BJ, MP 2, LCD 2, Web 1.0, Web 2.0, PV1 and PV2 have satisfied conditions for sustainable functionality development by open innovation ($\frac{dt_1}{dq/p}<0$ and $\frac{dp}{dx}<0$), MP1, LCD1 and LLBP have not satisfied these conditions resulting in the substitution of MP2, LCD2 and LBP/BJ, respectively.

Table 3
Diffusion parameters in major innovative goods and services.
Sources: [36,37].

		N	p	q	adj. R^2	$x=q/p$	$\varepsilon=\frac{dlnp}{dlnx}$	Trigger of new innovation
Printer[a]	LLBP (1975–1994)	0.16×10^4 (19.33)	5.43×10^{-3} (15.13)	5.8×10^{-2} (9.94)	0.999	10.7	0.03	
	LBP/BJ (1987–2005)	9.72×10^4 (166.57)	1.47×10^{-3} (2.27)	2.9×10^{-2} (37.96)	0.999	19.3	−0.35	
Mobile phone (1990–2006)	MP 1	3.82×10^4 (149.45)	0.12×10^{-1} (5358.9)	0.58×10^{-1} (2616.7)	0.999	5.0	2.59	Sky Walker (1997/10)
	MP 2	6.57×10^4 (170.24)	0.22×10^{-2} (1270.1)	0.35×10^{-1} (438.3)		15.6	−0.24	
LCD (2000–2008)	LCD 1	2.4×10^3 (1654.3)	0.3×10^{-2} (39.07)	0.2×10^{-1} (20.96)	0.999	7.3	0.60	
	LCD 2	2.4×10^3 (656.1)	0.4×10^{-4} (14.34)	0.8×10^{-1} (119.84)		1.9×10^3	−0.83	
Web (1993–2006)	Web 1.0	2.42×10^5 (145.87)	1.38×10^{-5} (8.35)	1.08×10^{-1} (58.33)	0.999	7.8×10^3	−0.87	RSS 2.0 (2003/7)
	Web 2.0	2.49×10^5 (75.66)	0.25×10^{-5} (2.60)	0.55×10^{-1} (22.74)		22.0×10^3	−0.89	
Photovoltaic Solar Cell (1976–2007)	PV 1	0.50×10^5 (8.81)	19.36×10^{-5} (3.87)	2.66×10^{-1} (45.22)	0.999	0.1×10^4	−0.83	NGPVs (2006)
	PV 2	12.71×10^5 (8.82)	0.04×10^{-5} (5.72)	4.11×10^{-1} (47.89)		105.4×10^4	−0.92	

[a]Since the period of co-existence of LLBP and LBP/BJ was limited, simple Bass model was used for respective innovation.
[b]Figures in parentheses indicate t-value. All demonstrates statically significant at the 5% level.
[c]LLBP: Large-scale Laser Beam Printer; LBP: Laser Beam Printer; BJ: Bubble Jet Printer; MP: Mobile Phone; LCD: Liquid Crystal Display; Web: Internet dependency based on the number of co.jp domains; and PV: Photovoltaic Solar Cell.
[d]Sky Walker: triggered e-mail transmission by mobile phone; RSS 2.0 (Really Simple Syndication): triggered publishing updated works in a standardized form as blog and video; NGPVs (Next Generation PV System): triggered acceleration of customers initiative in PV development and introduction by means of highly advanced next generation technology.

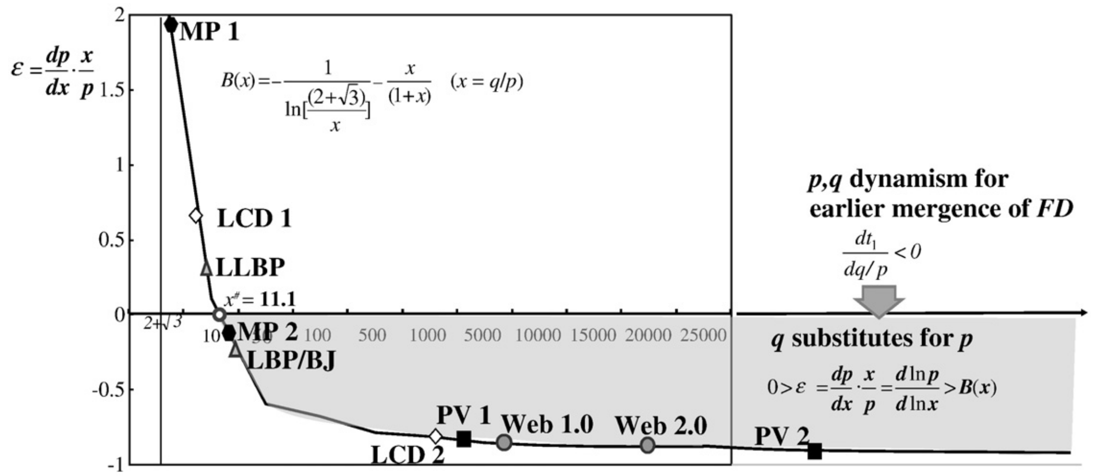

Fig. 8. Conditions for sustainable functionality development.

In contrast with PV and innovative goods and services on the web, which depended largely on cumulative learning from preceding innovations in semiconductors and networking technologies, MP1, LCD1 and LLBP were unique product innovations that developed independently, resulting in the sharp distinction.

Fig. 8 demonstrates that a high ratio of q/p (imitator/innovator) in revolutionary or high-risk innovations with a strong propensity for cumulative learning through imitator substitution for innovator typically was observed in the innovations in web and PV. This further supports the hypothetical view described in the mathematical model and demonstrates the significance of an open innovation.

Fig. 9 demonstrates new functionality development frontier expected to be explored by attaining sustainable functionality development by imitator (follower) substitution for an innovator (leader) in open innovation. Noteworthy

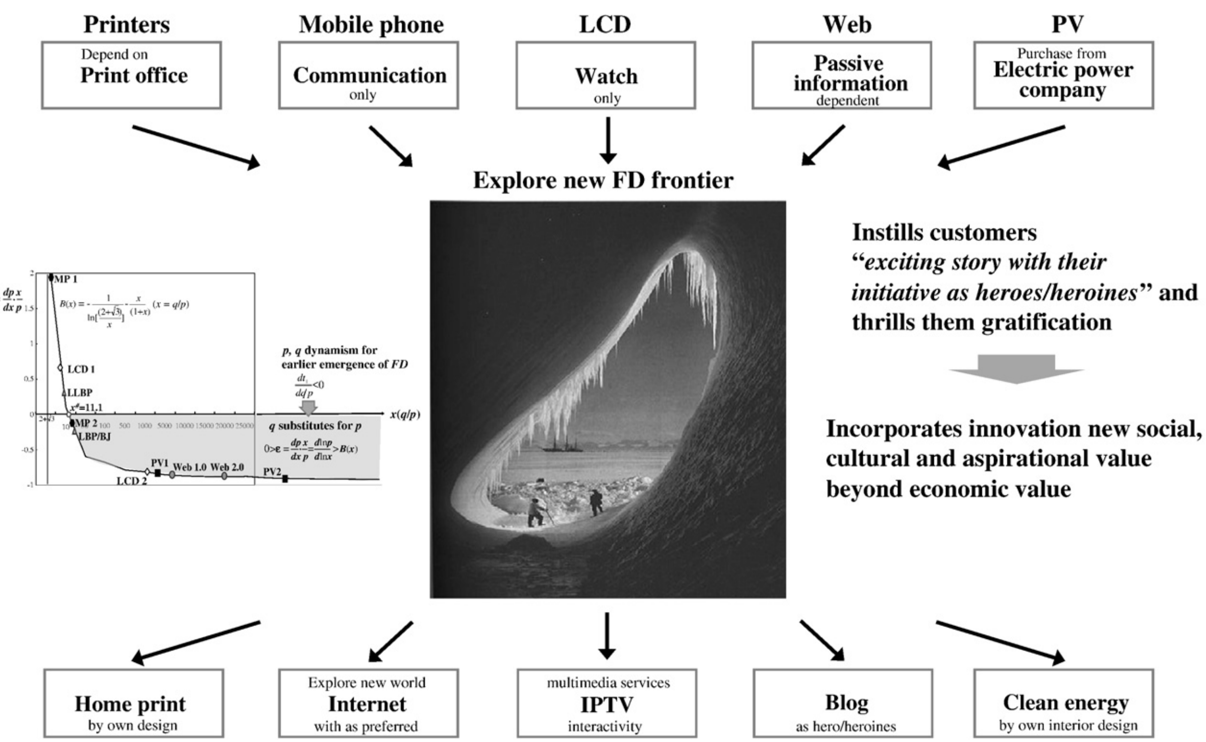

Fig. 9. New functionality development frontier.

features of the new functionality development frontier typically observed in each respective innovation can be summarized as follows:

(i) Printers: Shifting from dependency on print office to home print by own design.
(ii) Mobile phone: Shifting from a communication oriented world to exploring new world preferring Internet connectivity.
(iii) LCD: Shifting from passive “watching” world to interactive multimedia services.
(iv) Web: Shifting from passive information dependent world to a consumer-centric marketplace where consumers are co-producers.
(v) PV: Shifting from purchasing electric power from a utility company to creating eco-society by generating clean energy by own interior design.

This suggests a new process of innovation that is consumer-centric and consumer driven. Sustainable functionality can be enabled in this new paradigm as a consequence of open innovation.

7. Conclusion

This paper analyzed the necessary conditions enabling firms to prolong “functionality development” or innovation with participation from the marketplace. The focus was on describing mathematically the sustainable functionality development in order to enable firms to remain competitive in a highly competitive and resource constrained marketplace. This was an effort to mathematically describe and extend the open innovation theory.

By demonstrating that functionality development decreases as time passes, it was shown that timing for functionality development emergence and its governing factors were crucial to firm strategy and survival. This extended open innovation theory by describing the external conditions for stimulating the internal and external knowledge flows and enabling firms to compete.

Based on this, mathematical analysis which incorporated a diffusion function was used. Through this analysis it was identified that the early emergence of functionality development was the critical path for firms' sustainable functionality development. Furthermore, this depended on cumulative learning from the preceding innovation. These results enabled further analysis of the Bass model leading to the identification of imitator (follower) substitution for innovator (leader) as a necessary condition for the early emergence of functionality development. Identifying this factor extends our knowledge of the process and theory surrounding open innovation and conditions which need to be present for it to be a successful process.

Given the open innovation dynamic described, an empirical analysis was conducted utilizing a newly developed Bi–Bass model and taking the successive innovations in some of Japan's leading innovative goods and services such as printers, mobile phone, liquid crystal display (LCD), the web and photovoltaic solar cell (PV).

Noteworthy findings from this analysis include:

(i) Given the declining nature of functionality development, the sustainability of functionality development was essential for a firm's competitiveness and this depended on the early emergence of functionality development as the extended theory suggested,
(ii) The early emergence of functionality development depended on cumulative learning from preceding innovation and depended on imitator (follower) substitution for an innovator (leader) that enhanced the level of functionality development,
(iii) This substitution corresponded to the dynamics described in the open innovation process of successfully managing external and internal knowledge flows to quickly achieve innovation in the marketplace, and
(iv) Consequently, functionality development through imitator (follower) substitution for an innovator (leader) was critical for a firm's competitiveness in the open innovation environment. Therefore, the model confirmed the open innovation theory and extended it to include specific conditions.
(v) Finally, an empirical analysis taking Japan's leading innovative goods suggested that in contrast to the consistent sustainability in open innovation in high-risk, revolutionary innovations such as web and PV, the first phase of innovations in products such as printers, mobile phone and LCD did not demonstrated sustainable functionality development in open innovation.

These findings suggest the following policy and strategic implications concerning sustainable functionality development for firms in order to enhance competitiveness leveraging open innovation.

(i) The early undertaking of the new innovation is significant for a firm's sustainable profitability,
(ii) Open innovation cannot be maintained only by a firms own internal innovation resources but cumulative learning depends on the preceding innovation as well as external knowledge flows,
(iii) The effective utilization of external resources including, spillover technology through increased assimilation capacity, is essential,
(iv) The hybrid management of technology aimed at fusing internal strengths and the effects of external resources utilization is critical,

(v) Consistently prolonging functionality development is important in enhancing a higher level of functionality development. This in turn induces the acceleration of an earlier emergence of functionality development leading to a competitive virtuous cycle, and

(vi) The new functionality development, attained through sustainable functionality development in open innovation may assist firms in creating value in a post-mass-consumption society.

Further research should focus on an in-depth analysis identifying the similarity and disparity of the functionality development dynamism between diffusion models with different characteristics. This could further refine our mathematical description and understanding of the process of open innovation in different business settings.

Appendix

Appendix 1. The point of the chasm in the logistic growth model and its implication in the Bass model

Following the pioneer work by Rogers [31], the size of early adopter categories (16%) corresponding to the point of the chasm can be identified as following two diffusion models:

(i) Logistic growth model

In the logistic growth model, the inflection point $t_1$can be depicted as follows:

$$t_1 = \frac{ln\left(2-\sqrt{3}\right)b}{a}$$

Utilizing the above inflection point, the point of the chasm can be calculated as follows:

$$S = \int_0^{t_1} \frac{dY}{dt} dS = [Y]_0^{t_1} = \left[\frac{N}{1+be^{-at}}\right]_0^{t_1} = N\left[\frac{1}{1+\frac{1}{2-\sqrt{3}}} - \frac{1}{1+b}\right] = N\left[\frac{2-\sqrt{3}}{3-\sqrt{3}} - \frac{1}{1+b}\right]$$

Given the initial level of diffusion $N/(1+b) = 0.05\ N$, the size of early adopter categories is equivalent to 16% as follows:

$$\frac{S}{N} \approx 0.16$$

(ii) Bass Model

The inflection point t_1 in the Bass model can be depicted as follows:

$$t_1 = \frac{1}{(p+q)} ln\left[\frac{q/p}{(2+\sqrt{3})}\right] \qquad S = \int_0^{t_1} \frac{dY}{dt} dS = [Y]_0^{t_1} = \left[\frac{N(1-e^{-(p+q)t)})}{1+\frac{q}{p}e^{-(p+q)t}}\right]_0^{t_1} = N\left[\frac{1-(\frac{2+\sqrt{3}}{q/p})}{1+2+\sqrt{3}}\right] = N\left[\frac{1-(\frac{2+\sqrt{3}}{q/p})}{3+\sqrt{3}}\right]$$

Given the ratio of $q/p = 15.36$, the size of early adopter categories is equivalent to 16% as follows:

$$\frac{S}{N} \approx 0.16$$

Based on the data of Bass [28], Mahajan et al. [32] demonstrated that the size of adopter categories utilizing the value of q/p as 11.4 (steam irons), 16.8 (water softener), and 17.6 (automatic coffee maker), respectively. In line with this analysis, the point of the chasm can be observed when new functionality development emerges. The point of the chasm utilizing the logistic growth model can be also depicted.

Appendix 2. Proportional relationship between gross technology stock t and time t

The gross technology stock is measured by the following equation. [38].

$$T_t = R_{t-m} + (1-\rho)T_{t-1} \quad \text{(A1)}$$

where T_t: technology stock at time t; R_t: R&D investment at time t; m: time lag between R&D and commercialization; and ρ: rate of obsolescence of technology.

Eq. (A1) can be expressed by the following equation at the initial period:

$$T_0 = R_{1-m} / (\rho + g) \quad \text{(A2)}$$

where g: growth rate of R&D investment at the initial period.

$$T_t = R_{t+(1-m)} / (\rho + g), T_{t-1} = R_{t-m} / (\rho + g)$$

Thus, technology stock at time t can be depicted as follows:

$$T_t = R_{t-m} + \frac{1-\rho}{\rho+g}R_{t-m} = R_{t-m}\left(1 + \frac{1-\rho}{\rho+g}\right) = \frac{1+g}{\rho+g}\cdot R_{t-m} = R_0(1+g)^{t-m}\cdot\frac{1+g}{\rho+g} \tag{A3}$$

Given that $g \ll 1$ and ρ and g are stable, Eq. (A3) can be developed as follows[7]:

$$T_t = R_0[1+(t-m)g]\cdot\frac{1+g}{\rho+g} = R_0(1-mg+gt)\cdot\frac{1+g}{\rho+g} = R_0(1-mg)\cdot\frac{1+g}{\rho+g} + R_0 g\cdot\frac{1+g}{\rho+g}\cdot t = \alpha + \beta t \tag{A4}$$

where $\alpha = R_0(1-mg)\cdot\frac{1+g}{\rho+g}$ and $\beta = R_0 g\cdot\frac{1+g}{\rho+g}$.

Therefore, a proportional relationship between gross technology stock T and time t can be observed as depicted by Eq. (A4).

Appendix 3. Identification of the crossing point and ceiling of the boundary

From previous analysis of the boundary function $B(x)$, the zero of this function is depicted as follows:

$$B(x) = -\frac{1}{ln\left[\frac{(2+\sqrt{3})}{x}\right]} - \frac{x}{(1+x)} = 0 \tag{A5}$$

This is equal to

$$-\frac{1}{ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right]} - \frac{x}{(1+x)} = 0 \iff -ln\left[\frac{\left(2+\sqrt{3}\right)}{x}\right] = \frac{1}{x}+1 \iff -ln\left(2+\sqrt{3}\right) + lnx = \frac{1}{x}+1 \Leftrightarrow lnx - \frac{1}{x} = 1 + ln\left(2+\sqrt{3}\right) \Leftrightarrow x = e^{\left(\frac{1}{x}+1\right)}\left(2+\sqrt{3}\right) \tag{A6}$$

Thus, $x \approx 11.1$. Since $B(x) = -\frac{1}{ln\left(2+\sqrt{3}\right)-lnx} - \frac{1}{\left(1+\frac{1}{x}\right)}, \lim_{x\to\infty} B(x) = -1$.

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